ENTRANCE OF A STRONG SHOCK WAVE INTO A WEDGE-LIKE CAVITY

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Some special features of multiple Mach reflections of strong shock waves from the converging walls of a shock tube are investigated. The intensity of the visible radiation is found to be 1000 times greater than that of the initial wave. The brightness and duration of the glow and also the plasma density in the vicinity of the cavity vertex are also found to be much greater than those observed in normal reflection.

1. Among the methods of achieving high temperature, velocity, and other extremal parameters in various media, special interest attaches to the use of cumulative effects, in which the density distribution of highly excited energy becomes sharply non-equilibrium.[1] The pronounced appearance of a similar effect was expected upon the entrance of a shock wave into a channel with walls which converge at sufficiently small angles. Under these conditions (see the idealized Fig. 1) it is necessary that multiple generation of Mach reflections take place,[2-4] in which the frequency of appearance of new Mach configurations and their velocity in the vicinity of the vertex angle tend to infinity together with the values of the density, entropy and energy (thermal and vortex), if the liquid in the wedge-like cavity is assumed ideal and compressible. One can mentally extend this picture of the amplification of the shock front up to a multi-angular shock front which converges on a point (Fig. 2); this allows us to develop a nontrivial analogy with the "collapse" of a cylindrical shock wave to its axis (transition to sufficiently large angles destroys the analogy).

For constant $C_p/C_V = 1.2$, the parameters of an ideal gas behind the shock front of a cylindrical shock wave change according to the continuous law:[5]

$$T''/T' = p''/p' = (R'/R'')^{0.322} \to \infty \quad \text{as} \quad R'' \to 0,$$

here ρ_f = const, ρ_f denoting the density on the shock front.

The discontinuous process of amplification of a shock front by multiple Mach reflections (for the same C_p/C_V) can be expressed by the law (see below, Eq. (2)):

$$(R'/R'')^{0.8} \geqslant T''/T' = p''/p' \geqslant (R'/R'')^{0.42} \to \infty \quad \text{as} \quad R'' \to 0$$

(ρ_f = const), where the upper estimate corresponds to the limiting large angle of growth of the Mach

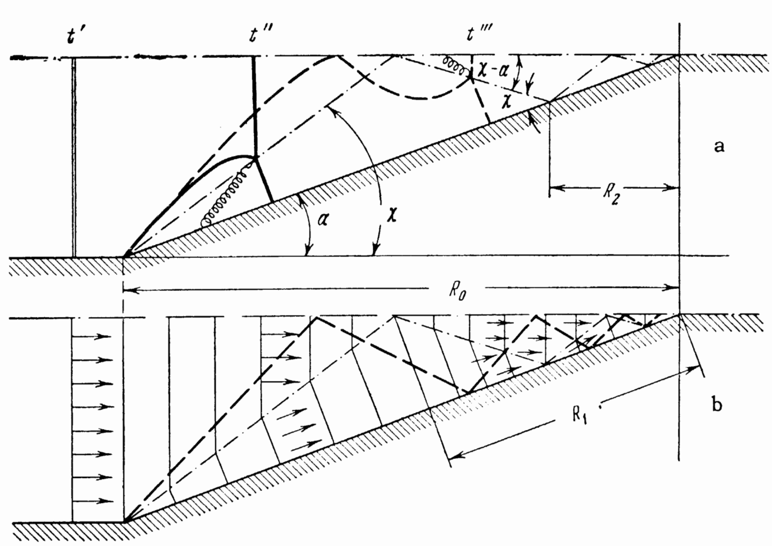

FIG. 1. a – times: t' – plane undisturbed shock front, t'' – after formation of the first generation Mach cone, which grows at an angle χ and the reflected wave, which is joined to the angle α (behind the undisturbed front, the flow is supersonic in the coordinate system of the vertex angle), t''' – after disappearance of the initial front, when $R > R_1$ and the second generation Mach cone has arisen, with a set of reflected waves (heavy dotted line). The spiral between the third point and the wall is the contact discontinuity. b – position of the shock wave at a later time. The thin dashed line is the trajectory of the third point, the heavy dashed line is the system of reflected waves at the instant of arrival of the shock front at the cavity vertex. The arrow indicates the direction of propagation of the shock front at different times.

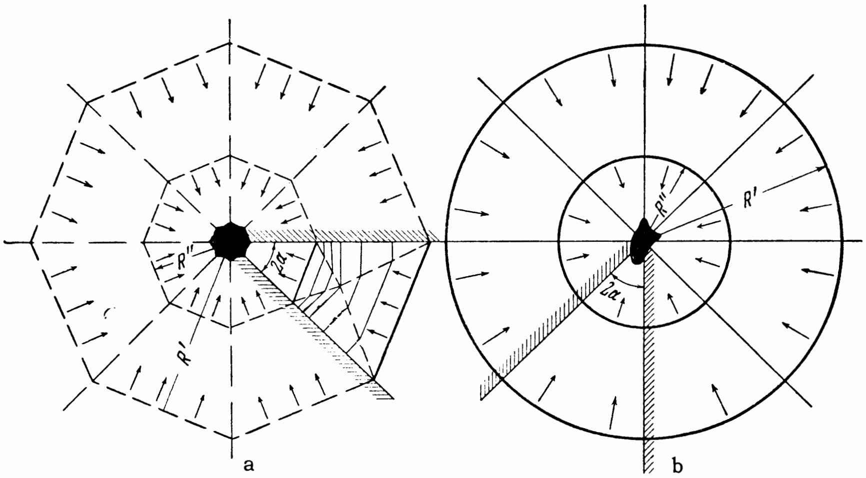

FIG. 2. Analogy between the angular "collapse" and the entrance to the wedge-like cavity. a – fictitious uniform collapse of a multiangular shock front: the excitations cannot greatly disturb the symmetry of the process (the black spot), b – fictitious entrance into the wedge-like cavity. The excitations (the role of which is symbolized by the spot) can appreciably disrupt the symmetry of the process, preventing the achievement of high velocities of the "collapse."

cone, equal to 43.5°, and the lower, to the minimum possible—35.2° (see Fig. 1 and below).

The shock front, which has the shape of a regular polygon, not only increases in strength much more rapidly than for a circular shape, but is also more stable. The increase in stability is brought about by the large a priori symmetry of the polygonal front that is formed (Fig. 2), which means the elimination of the contribution of the lower harmonics of the excitations of the shock front to the development of instabilities which prevent the achievement of "infinities." However, if the instability of the process of collapse to a point is produced principally by sufficiently high harmonics (with frequencies appreciably exceeding π/α, where α is the half angle at the vertex of the wedge), then the wedge or the cone-shaped variant presents no advantage other than that of technology, compactness, etc., in the particular problem.

The process of Mach reflection has not yet yielded to calculation, even in the self-similar aprroximation,[6] and certain general topological laws in the picture of Mach reflection are unknown. The known quantitative results are based on such a self-similar idealization in which the contact discontinuity behaves as in the case of a weak incident wave, although observations with strong waves indicate a very peculiar behavior of the flow in the region of encounter of the contact discontinuity with the wall: the contact discontinuity is "twisted." The role of this "twist" in the development of a strong Mach reflection is also seen from the failure of the attempt to prevent instability of the contact discontinuity in computer calculation by the introduction of a special term of "surface tension" into the equation—the self-similarity continued to be violated.[6]

However, the defects of the theory do not prevent a knowledge of the range of possible angles of growth of the Mach cone, which cannot grow more rapidly than at the critical angle of inclination of the wall (see Table I) which is determined by a known cubic equation,[2] or more slowly than at the angle of motion of the intersection point of the incident wave with the sound signal from the point of beginning of the reflection. K. E. Gubkin kindly drew our attention to this point. One can see from Table I that these estimates coincide as $C_p/C_V \to 1$.

If a Mach cone of arbitrary origin grows at a particular angle χ = const,[1)] then the temperature achieved in the vicinity of the vertex of the wedge-like cavity can easily be estimated. Up to the moment of reflection of the shock front from the vertex of the wedge-like cavity, the growth of the temperature and pressure p behind the shock front is accomplished in "jerks," along with the velocity of the front D. The total number of "jerks" is equal to the number of generations of Mach cones and can be estimated (see Fig. 1) by the smoothed relation

$$n = \log\frac{R_0}{R_{min}} \Big/ \log\frac{\sin\chi}{\sin(\chi-\alpha)}. \qquad (1)$$

Consequently,

$$\frac{T_n}{T_1} = \frac{p_n}{p_1} = \left[\frac{D_n}{D_1}\right]^2 = \left[\frac{\cos(\chi-\alpha)}{\cos\chi}\right]^{2n} = \left(\frac{R_0}{R_n}\right)^{2k}$$
$$\left(k = \log\frac{\cos(\chi-\alpha)}{\cos\chi} \Big/ \log\frac{\sin\chi}{\sin(\chi-\alpha)}\right), \qquad (2)$$

inasmuch as the following relations are valid[2]

1)This is plausible, inasmuch as the limiting estimates of χ depend only on values of κ, which change but little under the conditions of the experiment – according to the shock adiabats of N. M. Kuznetsov for air (cited by I. V. Nemchinov and M. A. Tsikulin [8]).

Table I

f	χ_{max}	χ_{min}	κ
1	59	43	3.0
2	56	41.4	2,0
3	53.5	40.3	1.67
5	50.03	38.3	1.40
6	48.3	37.5	1.33
7	46.9	36.9	1.29
10	43.54	35.2	1.20
14	40.47	33.5	1.14
16	39.28	33	1.125
18	38.25	32.27	1.11
99	25.5	23.5	1.02
∞	0	0	1

Remarks: f — effective number of degrees of freedom of the molecule of the medium; $\kappa = C_p/C_v = (f+2)/f$; χ_{max} — upper estimate of the angle of growth of the Mach cone, equal to the limiting angle of inclination of the wall α, calculated for various f or κ according to the cubic equation (63.7) of [2]; $\chi_{min} = \arccos[(f+1)/(f+\sqrt{f+2})]$ = lower estimate of the angle of growth, identical with the real value of χ as $\alpha \to 0$ for any f (the geometric sense of the angle is clear from Fig. 1).

for shock waves (for f = const):

$$\frac{T}{T_0} = \frac{p}{p_0} = M^2\frac{f+2}{f+1} \sim D^2, \quad \rho \neq \rho(D).$$

Upon reflection from the vertex angle, the temperature should undergo still one more "jerk," which can be estimated by extrapolation of the numerical calculations of the reflection of a diverging cylindrical shock wave (see, for example, [9,10]) to our value of κ. This still gives an approximate tripling of the temperature, that is, as an idealized estimate, which does not take into account the effect of radiation, of the boundary layer and of other disruptions of the ideal nature of the plasma, we get

$$T_{max} \approx 3T_1\{\cos(\chi - \alpha) / \cos\chi\}^{2n} = 3(R_0 / R_{min})^{2k}, \quad (3)$$

where the number n of Mach reflections is determined from (1) by the value of R_{min}, that is, the distance from the vertex angle of the wedge-like cavity to the point of formation of the last generation of Mach configurations.

Under conditions corresponding to our experiments, one can quite reasonably make the choice R_{min} = 1 mm, since this number represents twice the length of the mean free path of the air molecules at a pressure of $p_0 \approx 0.1$ mm Hg, in front of the shock front, in the principal series of our experiments, and a minimum thickness of the shock front again equal to two path lengths (without the effect of radiation). An idealized estimate predicts an increase in the temperature of approximately an order of magnitude in comparison with the temperature T_1 on the front of the wave entering the cavity. The length of the latter amounted to R_0 = 50 mm.

It is important to note that after reflection of the shock front from the vertex, the gas behind the shock front being exhausted (comparatively slowly) upward along the flow will experience further isentropic compression by a factor of about 2—4. However, this compression does not lead to further significant growth in the plasma temperature, similar to the plasma in our apparatus, when the value of κ is close to unity, i.e., the isentropic process is close to isothermal (see the Appendix).

2. Shock waves were obtained from an electric spark discharge in an iron tube with inside diameter ~110 mm. The stored energy was ~8000 joules; about 3000 joules was released in the discharge space, 80% of it in 8.5 microseconds.

In this series of experiments the tube consisted of two sections of length up to 550 mm; one Plexiglas section was connected to the end of a second, and had a rectangular cross section 50 × 50 mm and length 320 mm. An insert was placed in the latter, in the form of a wedge-like cavity with an angle of 40° at its vertex. The total distance from the discharge region to the vertex of the wedge-like cavity amounted to 1300 mm.

The tube was filled with atmospheric air. The initial pressure in front of the shot was measured by means of a McLeod manometer. After each shot, the tube was refilled with air and again evacuated to one of three initial pressures: 0.1, 0.2 and 0.5 mm Hg.

From the experiments described earlier on the study of the propagation of shock waves from electric spark discharges in tubes we established the fact that at an initial pressure in the tube below 1 mm Hg the shock front was identical with the front of the air glow. Therefore, the velocity of the shock front was measured in the present experiments by its time of passage through a known distance by means of a high speed SFR camera with a mirror angular velocity ω = 60,000 rpm.

One of the traces obtained by such means is reproduced in Fig. 3. It is seen from the picture that the slope of the front in the region between the marking pips is practically constant and can (with sufficient accuracy) determine its velocity in the region between the pips.

The measured velocities of the shock fronts at the location of the wedge cavity were shown to be equal to 22.5, 15.8 and 6.3 km/sec, respectively, with accuracy to within 16% for the initial pres-

FIG. 3. Recording of the initial shock wave, $p_{init} = 0.1$ mm Hg, distance between markers, 30 mm, velocity of shock wave ~ 22.5 km/sec, amplification of the brightness in the lower part due to normal reflection of the shock wave from the plane wall.

sures of 0.1, 0.2 and 0.5 mm Hg, respectively.

The development of the picture of the entrance of the shock wave into the wedge-like cavity was photographed by means of the SFR camera in the time magnification mode, with a rate of 2×10^6 frames/sec.

The visible region of the shock wave spectrum in the cavity was photographed by an ISP-51 spectrograph with a mean dispersion of 30 Å/mm. The cavity was focused on the input slit of the spectrograph by means of two lenses and a system of tilting mirrors, so that a scan of the shock wave spectrum along the length of the cavity was obtained on film. The spectrum of an iron arc and the spectrum of a ribbon-filament lamp, exposed through a 9-step reducer, were recorded on the same film.

Time sweeps of the separate parts of the spectrum of the shock wave for different distances from the vertex of the wedge-like cavity were obtained by means of a system of two monochromators, photoelectric apparatus for them, and an OF-17M oscillograph. The system was calibrated in absolute units by means of the ribbon-filament lamp, with an accuracy to within 6%.

Along with the basic series of experiments, similar measurements were carried out in calibration experiments—for normal reflection of the shock wave from a plane wall (in a section without the insert).

3. Figure 4 shows a typical picture of the entrance of a strong shock wave into the wedge-like cavity. The brightness of the illumination strongly increases upon encounter of the shock wave with the inclined wall (the front of the shock wave itself is barely seen in the image). This increase in the illumination intensity is interpreted by us as the generation of Mach cones upon irregular reflection of the shock. It can be noted that as the shock wave travels into the depth of the cavity, the height of the illuminated region above the wall increases, which should be characteristic for the Mach configuration (see Fig. 1). The measured angle of inclination of the upper boundary of the illuminated region relative to the wall of the cavity gave values of the angle of advance of the Mach cone $\chi \lesssim 40°30'$ for an initial pressure p_0 in the tube equal to 0.1 mm (we note that, according to the data given in the work of Nemchinov and Tsikulin,[8] $\kappa = 1.15$ behind the shock waves under our conditions). This value differs significantly from that obtained by Fletcher et al[11] for a shock wave with $\kappa = 1.4$. We add that we have not yet succeeded in establishing the reason for the skewness of the shock front at its entrance to the cavity (see Fig. 4).

Photometry of the film with the frames of the scan of the picture of the shock front entering the cavity showed that the density of the film has a step-like character along the length of the cavity. At least four regions were recorded with different densities, i.e., four zones of ever increasing

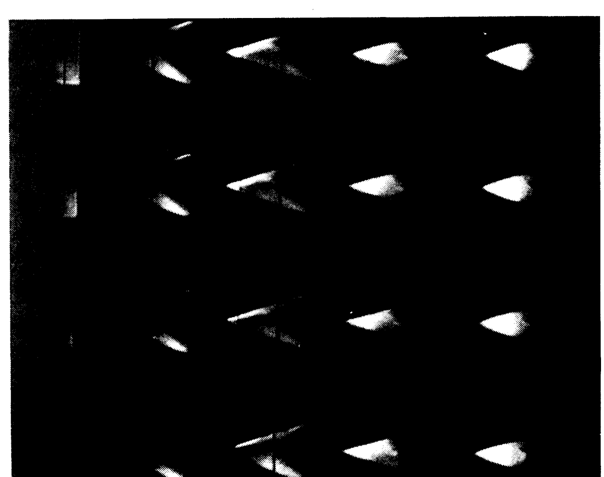

FIG. 4. Entrance of the shock front into the wedge-like cavity. $p_{init} = 0.1$ mm Hg, velocity of scan, 2×10^6 frames/sec.

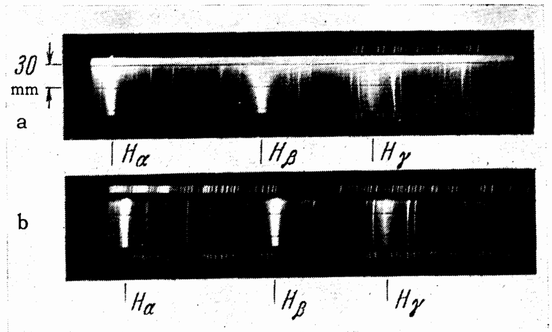

FIG. 5. Integral spectra of the plasma glow: a – in the wedge-like cavity; b – for normal reflection from a plane wall, $p_{init} = 0.1$ mm Hg.

brightness. This is precisely what is expected in the generation of multiple Mach configurations (see Fig. 1). Inasmuch as the region of weakest glow corresponds to the incident shock wave, one can draw the conclusion that no less than three successive Mach reflections take place in the wedge-like cavity. The maximum brightness recorded in the vertex angle of the cavity is about 1000 times brighter than the glow of the incident shock wave front (for normal reflection of the shock wave from a plane wall, an increase in brightness of about 25 times is recorded).

The scan of the spectrum of the plasma glow along the axis of the cavity is shown in Fig. 5a. It is seen that the intensity of the continuous background increases as we proceed toward the vertex angle of the cavity, the broadening of the visible spectral lines increases and the lines disappear in the noise in the vicinity of the vertex. At a distance of ~ 10 mm from the vertex angle of the cavity, over 100 spectral lines are identified, principally belonging to singly-ionized atoms of nitrogen and oxygen. The lines of the Balmer series of hydrogen are strongly broadened and diffuse, and only H_α and H_β are observed. Photometry of the spectra at an initial pressure in the tube of ~ 0.1 mm Hg showed that only the H_α line appears above the noise at a distance of ~ 0.5–1.0 mm from the vertex angle of the cavity; all the other lines are masked by the noise.

For comparison, the spectrum of a shock wave (for the same initial pressure in the tube) reflected from plane walls is given in Fig. 5b. Here the intensity of the continuous noise is much less, the diffusion of the NII and OII lines is absent, the hydrogen lines are less broad, and the H_γ line is also observed. By photometry of the wave reflected from a plane wall we determined the shapes of the H_α, H_β and H_γ lines and the relative intensity of the NII and OII lines.

Figure 6 shows a typical time sweep of the spectrum of the plasma glow near the vertex angle of the cavity. This scan was carried out for two portions of continuous noise corresponding to $\lambda_1 = 4000$ Å and $\lambda_2 = 5200$ Å for a distance ~ 1–1.5 mm from the vertex angle and at an initial pressure in the tube of ~ 0.1 mm Hg. The widths of the entrance and exit slits of the monochromators were 0.02 mm in all measurements. In Fig. 6, it can be seen that the glow of the continuous background has the character of short time bursts of very high intensity (the time pips occur every 2 microseconds). Tables II and III give the absolute values (measured from oscillograms of the time sweeps of the individual portions of the spectrum) of the spectral brightnesses and the characteristic times of the plasma glow in the wedge-like cavity, and also for normal reflection of the shock wave from the plane wall. The error in the determination of the absolute values of the spectral brightnesses is estimated by us to be 11%.

4. Substituting the value $n = 3$ in the estimating formula (4), we find that at a velocity of the initial shock wave ~ 22 km/sec the plasma at the cavity vertex should reach a temperature of ~ 2.7 $\times 10^5$ °K. The brightness temperature of the plasma was calculated from the absolute value of

FIG. 6. Oscillograms of the time sweep of the spectrum of the plasma glow close to the cavity vertex. $p_{init} = 0.1$ mm Hg. I – $\lambda_1 = 4000$ Å; II – $\lambda_2 = 5200$ Å, time markers spaced every 2 microseconds.

Table II. Spectral brightness B_λ and time τ of decay of the glow to ½ maximum of B_λ for a plasma in wedge-like cavity ($p_{init} \approx 0.1$ mm Hg)

λ, A	Distance to vertex of cavity, mm	B_λ, W/A	τ, μsec	B_λ/B_λ^*	Remarks
4000	1–1.5	69.0	0.8	57.5	Continuous background
5200	1–1.5	25.6	0.8	42.5	Continuous background
4861	1–1.5	33.2	0.8	11.0	Continuous background with Hβ line
5200	12	6.1	1.6	47.0	Continuous background
4861	12	11.4	3.0	15.2	Continuous background with Hβ line
4000	18	2.4	3.0		Continuous background
5200	18	1.1	3.0		Continuous background
4861	18	2.8	3.0		Continuous background with Hβ line
5200	42	0.9	3.0		Continuous background
4861	42	4.0	3.0		Continuous background with Hβ line

Table III. Spectral brightness B_λ^* and times τ of plasma for normal reflection of the shock wave from a plane wall ($p_{init} \approx 0.1$ mm Hg)

λ, A	Distance to vertex of cavity, mm	B_λ^* W/A	τ, μsec	Remarks
4000	1.5	1.2	1.5	Continuous background
5200	1.5	0.6	1.5	Continuous background
4861	1.5	3.0	20	Continuous background with Hβ line
5200	12	0.13	2.0	Continuous background
4861	12	0.75	20	Continuous background with Hβ line

the spectral brightness of the continuous background for the vicinity of the vertex angle of the cavity. Values of the brightness temperature for different portions of the spectrum are given in Table IV.

Thus the brightness temperatures are practically identical in three different parts of the spectrum. It can be assumed that the plasma close to the vertex angle of the cavity radiates as a gray body with a brightness temperature of 35.2×10^3 °K. Estimates for the paths of radiation from the Kramers formula give a value in our case of the order of several centimeters. Attention is called to the strong difference of the measured temperature of the plasma from that expected according to estimates by (4). However, these estimates did not take possible energy losses into account. For a brightness temperature of 3.5×10^4 °K, there are very large energy losses because of the radiation.

We now estimate the relation between the internal energy of the gas and the radiation losses in a small volume at the vertex angle of the cavity with dimensions $0.2 \times 0.2 \times 5$ cm, where, according to our estimate, one can expect high temperatures. According to Eq. (2), the velocity of the shock wave D_n at a distance of ~2 mm from the vertex of the cavity is equal to 40 km/sec for an initial pressure of 0.1 mm Hg. Gasdynamic calculations give a value of the temperature behind the shock front of 5×10^4 °K. According to [10], the value of $\kappa = 1.15$, i.e., the effective number of degrees of freedom is $f = 13$.

Table IV. Brightness B_λ and brightness temperatures of plasma at distances of 1–1.5 mm from the vertex angle of the cavity ($p_{init} = 0.1$ mm Hg)

λ, A	B_λ, W/A	T_{bright}, °K	Remarks
4000	69.0	$36.2 \cdot 10^3$	Continuous background
5200	25.6	$34.6 \cdot 10^3$	Continuous background
4861	33.2	$34.8 \cdot 10^3$	Continuous background with Hβ line
		$T_{av} = 35.2 \cdot 10^3$	

The internal energy of the gas in the region under consideration is

$$E_{int} = C_v T = \frac{f}{2}\frac{m}{\mu} RT \approx 3.6 \cdot 10^7 \text{ erg},$$

where R is the universal gas constant, μ is the molecular weight of the air, m is the mass of gas in the given volume for an ionic concentration in the cavity vertex of $\sim 5 \times 10^{18}/\text{cm}^3$. After reflection from the vertex angle of the cavity the energy increases by another factor of three (see above); i.e., we finally have as an estimate $E_{int} \approx 1.0 \times 10^8$ ergs.

Making use of the Stefan-Boltzmann formula, we estimate the value of the energy radiated through the lateral surface of our volume, $S \approx 3$ cm^2 for a brightness temperature of the plasma equal to 3.5×10^4 °K after a time $\tau \approx (2–3)\,10^{-7}$ sec (see Fig. 6):

$$E_{rad} = \sigma T^4 S \tau = 8.0 \cdot 10^7 \text{erg}.$$

Thus, for a brightness temperature of the order of 3.5×10^4 °K, the losses to radiation amount to a considerable part of the internal energy of the gas, which becomes the limit of further increase in the plasma temperature at the vertex of the wedge-like cavity.

The electron concentrations in the plasma are determined from the broadening of the lines of the Balmer series.

According to the data of Tables II and IV, one can assume that the radiation of hydrogen recorded by us came from the hot plasma and not from the layer near the wall. It is evident that the broadening and diffusion of the hydrogen lines are brought about by a linear Stark effect. The concentration of electrons N_e in the plasma near the vertex angle of the cavity was determined by the formula of Inglis and Teller, which takes into account the disappearance of the lines of the Balmer series of hydrogen because of the shift in the true limit of the series:[12]

$$\log N_e = 23.3 - 7.5 \log g^*.$$

It has been established by spectrophotometry that, for an initial pressure in the tube of 0.1 mm Hg, only the line H_α is clearly distinguishable against the background at a distance of 0.5—1 mm from the vertex angle of the cavity; i.e., $g^* = 3$. From this formula, we get

$$N_e = 5.3 \cdot 10^{19}\,\mathrm{cm}^{-3}.$$

Taking into account the possible inaccuracy in the determination of the complete absence of the H_β line, we get a lower estimate of the electron density at the cavity vertex:

$$N_e \approx 6.3 \cdot 10^{18}\,\mathrm{cm}^3.$$

A gasdynamic estimate of the density in the incident wave gives a value $N_e \approx 10^{17} - 10^{18}$, i.e., there is a one hundredfold increase in the electron density at the vertex of the cavity. For an initial pressure in the tube of 0.2 mm and 0.5 mm Hg, the electron concentration per cm^3 close to the vertex of the wedge-like cavity is estimated from the measured half-widths $\Delta\nu_{1/2}$ and the Holtzmark shapes of the H_β line[11] are reproduced in Table V.

Similar results for reflection from a plane wave are given in Table VI.

Attention is turned to the fact that the values of the electron concentrations given in Table VI are approximately an order of magnitude smaller than the values obtained from gasdynamic calculations for normal reflection of shock waves. This also ought to be the case, because the values of the electron concentrations given in Table VI are the average over the entire time of the plasma glow (the shapes of H_β are taken from photographs of integral spectra), but gasdynamic calculations give the maximum values.

Tables VII and VIII give the electron temperatures for the case of normal reflection of shock waves, computed from the relative intensities of the spectral lines NII and OII. The relative intensities were obtained by the method of photometric treatment of integral spectra. Inasmuch as the absorption is not known to us for lines which are sufficiently significant at concentrations of atoms $\sim 10^{18}$ cm^{-3}, we have selected in the calculation of the temperature pairs of lines with similar transition probabilities and similar intensities. In this

Table V

Experiment		Calculation	
p_{init}, mm Hg	$\Delta\nu_{1/2}$, sec^{-1}	N_e according to $\Delta\nu_{1/2}$, cm^{-3}	N_e according to shape, cm^{-3}
0.2	$1.14\cdot10^{13}$	$4\cdot10^{17}$	$4.5\cdot10^{17}$
0.5	$1.33\cdot10^{13}$	$5.2\cdot10^{17}$	$5.0\cdot10^{17}$

Table VI

Experiment		Calculation	
p_{init}, mm Hg	$\Delta\nu_{1/2}$, sec^{-1}	N_e according to $\Delta\nu_{1/2}$, cm^{-3}	N_e according to shape, cm^{-3}
0.1	$6.96\cdot10^{12}$	$2.7\cdot10^{17}$	$2\cdot10^{17}$
0.2	$6.75\cdot10^{12}$	$1.8\cdot10^{17}$	$2\cdot10^{17}$
0.5	$3.6\cdot10^{12}$	$8\cdot10^{16}$	$1\cdot10^{17}$

Table VII. Electron temperature T_e behind the shock wave ($p_{init} \approx 0.1$ mm Hg)

Wavelength λ, Å, of pair of lines	$A_i g_i \cdot 10^{-8}$, sec^{-1}	E_i, eV	$\log \frac{J_1}{J_2}$	$T_e \cdot 10^{-3}$, °K
N II				
5005.14	11.4	23.13	0.08	43.5
4630.5	4.5	21.15		
5005.14	11.4	23.13	0.655	38.2
4607.2	1.09	21.14		
5005.14	11.4	23.13	0.602	49.5
4601.5	1.41	21.15		
				$T_{av} = 43.7$
O II				
4591	12.7	28.36	1.746	43.5
4649.1	11.3	25.65		
4153	7.1	28.82	1.792	43.5
3973.3	5.57	26.56		
4132.82	4.53	28.83	1.996	42.2
4661.6	2.8	25.63		
				$T_{av} = 43.07$

Table VIII. Electron temperature T_e behind the shock wave ($p_{init} \approx 0.2$ mm Hg)

Wavelength λ, Å, of pair of lines	$A_i g_i \cdot 10^{-8}$, sec^{-1}	E_i, eV	$\log \frac{J_1}{J_2}$	$T_e \cdot 10^{-3}$, °K
N II				
5941.67	3.86	23.24	0.488	32.9
4601.49	1.41	21.15		
4630.55	4.5	21.15	0.50	33.2
5666.64	2.18	20.62		
5941.67	3.86	23.24	1.496	32.5
5679.56	4.43	20.66		
5941.67	3.86	23.24	1.805	33.2
5666.64	2.18	20.62		
				$T_{av} = 33.0$
O II				
4590.94	12.7	28.36	1.612	29.8
4649.15	11.3	25.65		
4590.94	12.7	28.36	1.835	34.8
4414.89	8.35	26.24		
				$T_{av} = 32.3$

case it can be assumed that the absorption coefficients in the lines are approximately identical and that the self-absorption does not bring in any large errors in the calculation of the temperature. The values of the oscillator strengths are taken from the work of Mastrup and Wiese.[14] It is seen from Tables VII and VIII that the temperatures determined from the nitrogen and oxygen lines do not differ appreciably. The mean value of temperatures for initial pressures equal to 0.1 mm Hg and 0.2 mm Hg are equal to 43.4×10^3 and 32.7×10^3 °K, respectively. The resultant temperatures are in agreement with the values calculated by means of gasdynamic representations, if it is taken into account that the error in the determination of the temperature from the relative intensities of spectral lines is estimated by us in the given case to have a value of 21%.

Thus, as the result of multiple, irregular (Mach) reflections of a strong shock wave entering into a wedge-like cavity, a significant increase in the plasma temperature is obtained, more than one hundredfold increase in the mass density and a 1000-fold increase in the brightness of the glow in comparison with the characteristics of the plasma behind the initial shock front. At the vertex of the wedge-like cavity, a plasma is formed which radiates as a gray body, with a brightness temperature equal to 35×10^3 °K.

In comparison with normal reflection from a plane wall (for the same initial parameters of the shock wave) an increase by a factor of about ten is observed in the electron density in the wedge-like cavity and a 50-fold increase in the glow brightness. The glow of the plasma created in a similar cavity is easily used as a source of high intensity radiation, the duration of which depends on the dimensions of the cavity, and the shape of which (wedge, cone, etc.) will depend on the specific case.

In conclusion, we consider it our pleasant duty to thank Prof. G. I. Pokrovskiĭ for suggesting the idea of the experiment, and also to K. E. Gubkin, Prof. K. Moravets and I. V. Nemchinov for valued discussions, and Z. N. Stepchenkov for calculations.

Addendum (September 9, 1964). At the instant of reflection of the shock front from the vertex of the wedge-like cavity, as also at the instant of reflection from the axis of a cylindrical shock wave, a peak temperature is reached (infinitely large if the wave is a mathematical discontinuity). The reflected wave is attenuated in proportion to its propagation; however, the further isentropic compression of the gas, which takes place in the vicinity of the vertex angle through the reflected shock wave (as also near the axis in the case of a cylindrical collapse), can lead to the appearance of a secondary strong temperature maximum (which should coincide with the density maximum), if κ takes a value, say, of about 1.67. Just such an effect was observed by V. F. D'yachenko and V. S. Imshennik as the result of numerical calculation of the cylindrical collapse of the shock wave (with a finite thickness of the front) in a plasma, reported at the fourth Riga conference on magnetohydrodynamics and plasma in June, 1964.[15] In our experiment, two maxima could be noted in the radiation intensity; the second was the stronger and also corresponded to the maximum density of the plasma.

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